Temperature detection circuit on the low-temperature superconducting coils

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Abstract Experimental Advanced Superconducting Tokamak (EAST) is the fully superconducting Tokamak. The EAST magnet system comprises 16 D-shaped toroidal field coils and 14 poloidal field coils which are cooled by supercritical helium at 4.2 K and 3.8 K. The temperature of superconducting coils is measured by Cernox as a new type low-temperature sensor, and monitored during the cooling and operation. The helium temperature can offer reference for quench signal. In this paper, a technique for the weak temperature signal measurement of superconducting coils is introduced, and its weak voltage is extracted from the intrinsic noise of the amplifier by the low-noise instrumentation amplifier, filter circuit, and high-linearity analog optocoupler. The temperature detection circuit works accurately and safely whether in cooling or operating process. This technique is an effective for the temperature detection on the low-temperature superconducting coils.

Key words Supercritical helium temperature, Temperature sensors, Weak signal measurement

1 Introduction

Experimental Advanced Superconducting Tokamak (EAST) as an advanced steady-state-capable experimental device for high temperature plasma research[1] is comprised of the superconducting poloidal field (PF) system, the toroidal field (TF) magnet system, the vacuum vessel, the cryostat, and the thermal radiation shield (Fig.1). The PF system contains the 14 coils located symmetrically about the equator plane, and the six inner PF coils form the central solenoid (CS) assembly. The TF magnet system has a toroidal array of 16 D-shaped coil producing 3.5 toroidal field at the 1.7-m plasma major radius[2].

The TF magnet systems are cooled with supercritical helium during the cooling and operation. Temperature at each point of magnet coil is obtained by using multiplex temperature sensor in coil different places. The cooling rate and the temperature difference between the various device components are strictly controlled, in order to basically cool them at the same speed and prevent the device insulation or device component damaging caused by excessive thermal stress. In the run-time, the critical temperature of the coil should be maintained to prevent its quench.

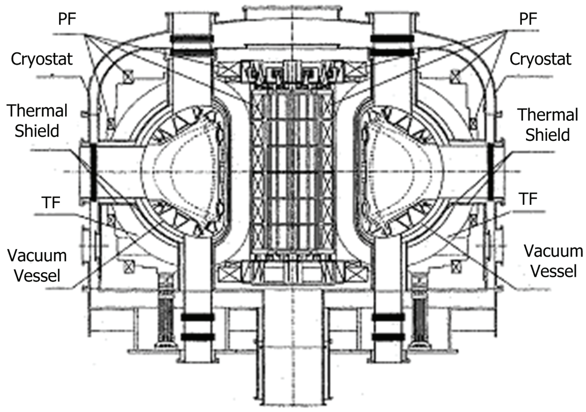

Fig.1 The EAST device.

During the experiment, the TF coils run in the steady-state mode, and the normal running current is 14.3 kA at 4.2 K; and 16.35 kA, 3.8 K. While the PF

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coils run in the pulse mode, the maximum current is 14.3 kA, and its time variation rate is 20 kA/s[3].

CX-1050AA, a new type of low temperature resistance sensor prepared by ceramic nitride oxide (CERNOX) is adopted to measure the coil systems. The standard temperature sensor, X11181, is calibrated by American Lake Shore Co.; and the others, by self-developed low temperature calibration device[4]. The Cernox is the negative temperature coefficient sensor, its calibrated temperature range is 3.5–300 K, and the scaled precision is better than that of 10 mK at 4.2 K[5]. The typical resistance and temperature are shown in Table 1.

Table 1 Typical resistance and temperature

Temperature / K	Resistance / Ω
4.2289	4151.3900
4.4835	3827.8561
4.7936	3500.9866
5.8710	2701.8991
8.9085	1677.2124
10.0243	1477.6202
20.0110	740.3153
64.5891	234.3619
99.8836	151.1221
199.1449	74.4220
304.3216	48.9961

Cernox thermometers are installed on the outer wall of the cooling pipe inlets and outlets in magnet coils and coil boxes. Figs.(2) and (3) show the quantity and installation positions of PF and TF coils. The measurement errors are reduced by the following steps[5]. Firstly, the Al_2O_3 powder and vacuum grease are added into the socket of thermometers to ensure that they have a good thermal contact with the detected objects. Secondly, the heat leakage along the measure line is reduced to prevent thermal radiation. Thirdly, the PF coils work in the pulse mode up to the highest PF current ramping rate of 20 kA/s, and the fast changing current can produce strong interfering signals. The shielding twisted-pair is adopted to avoid the electromagnetic interference. Fourthly, the thermometers are powered by high stability constant current source and measured by four-wire system.

On adopting the two-wire measurement, the constant current source generates voltage on the lead resistors (R_1, R_4), thus affecting the measure accuracy of a thermometer. As shown in Fig.4, the current source and voltage measure circuits are separated by using four-wire measurement. The R_1 and R_4 do not affect the current. The measure voltage is real across the thermometer because the circuit current through the R_2 and R_3 is very small, and the large input resistance of the operational amplifier and the lead resistors (R_2 and R_3) could be ignored.

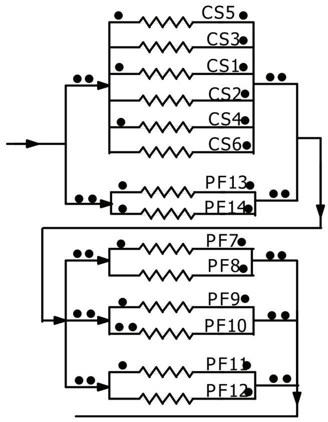

Fig.2 The CERNOX installation positions in the PF coils.

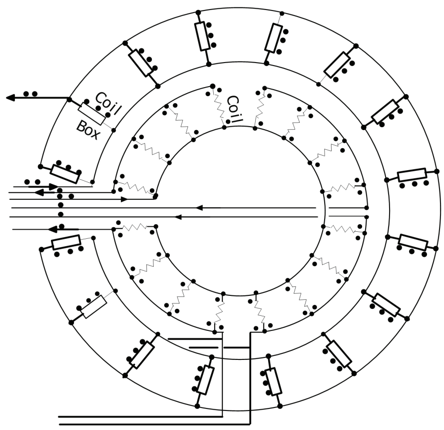

Fig.3 The CERNOX installation positions of TF coils.

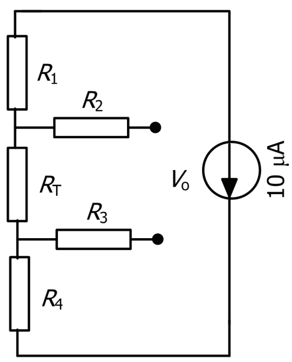

Fig.4 The four-wire measurement.

In order to eliminate the analog signal circuit noises which are caused by common ground interference such as the hidden ground loops and improper grounding in the measure and control systems, the signal pretreatment, amplification, filter and isolation should be considered.

The pretreatment should select the low-noise amplifier with high common-mode rejection ratio (CMRR) and the suitable filter circuit.

Analog signal isolation requires high standards for the signal transmission linearity and the gain temperature stability. It is difficult to realize analog signal linearity isolation.

The basic isolation approach includes synchronous voltage-to-frequency converter, linear transformer isolation, linear modulation and demodulation, and optocoupler linear amplification.

The first method works reliably under the limitation of the frequency bandwidth and signal transmission rate. The second has the property of good linearity and high isolation voltage, but its large volume is mainly confined to transmit the audio power signal. The third works with high frequency bandwidth and linearity, but the isolation voltage is less than 3 500 V. Ordinary optical couple is seldom used because of its narrow linear region and temperature stability.

To form low temperature superconductive coil detection circuit, we adopt the low noise and high CMRR amplifier, Butterworth second order filter with good flatness characteristic in the pass-band, high linearity, high isolation voltage up to 50 000 V, and temperature stability with temperature compensation optocoupler HCNR201. During the experiment, the 10-μA constant-current source applies to the sensor, and its output voltage is 0.45–0.6 mV at room temperature; and 40–50 mV at supercritical helium temperature. After 100-times amplification, the low-pass filter and isolation by high-linearity analog optocoupler, the conditioned signal is sent to 16-bit high-resolution data acquisition card. The computer completes real-time process and display.

2 Basic composition of temperature detection circuit

Figure 5 shows the block diagram of the temperature detection system. To match the best measure ranges of data acquisition card, millivolt signals from the temperature sensors should be amplified by two-stage amplifiers with each fixed gain of 10.INA217, the low-noise and high CMRR instrumentation, and OP07, the ultra low input offset voltage. The magnet system cools down from 300 K to 4.2 K at the average rate of 1 K/h. A designed low-pass filter circuit should avoid noise caused by the large current and the varying high electro-magnetic fields. The cool down rate and temperature signal response rate is considered when magnet system is quenched, the filter cutoff frequency is taken as 7.5 Hz. The PF coils run in pulse mode, and the maximum instantaneous terminal voltage of PF7 and PF8 is more than 3500 V. To ensure safety, an isolation device should be used to isolate the field and the data acquisition system, and separate the signal to a clean and safe signal subsystem ground[6]. To satisfy the isolation voltage, the HCNR201 with the high-linearity and 5 000 V isolation voltage analog opto-coupler is selected.

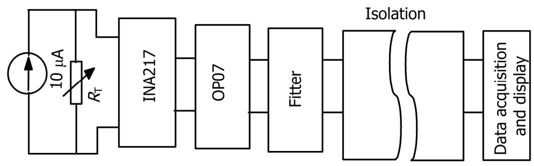

Fig.5 The block diagram of temperature detection system.

3 Amplifier unit

The INA217 as the preamplifier, which is a low-noise and low-distortion monolithic instrumentation, provides the superior performance in professional weak signal detection applications[7]. Current-feedback circuitry allows the INA217 to achieve wide bandwidth, excellent dynamic response over wide gain range, and unique distortion cancellation circuitry.

As shown in Fig.6, the gain for the INA217 is set with an external resistor (R_G), and expressed as G= 1+10000/R_G

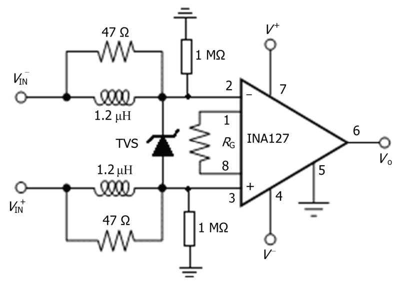

Fig.6 The amplifier circuit.

The input impedance of the INA217 is about 60 MΩ. Without a bias current return path, its inputs will float to a potential, which exceeds its common-mode range, thus saturating its input amplifiers. Two resistors with 1 MΩ can provide a balanced input with possible advantages of lower input offset voltage due to bias current and better common-mode rejection.

Very low source impedance can cause the INA217 to oscillate, and the sensor resistance is about 50 Ω at room temperature. An input network consisting of a small inductor and resistor can greatly reduce any oscillating tendency.

4 Filter circuit

A Butterworth filter has the maximally flat response in pass-band without the ripple distortion accompanying other implementations, such as the Chebyshev or Elliptic. Above the –3dB point, the attenuation is relatively steep with a slope of –20 dB/decade/pole.

Two second order Butterworth low-pass filters with cascade can control the transition sharpness from pass band to stop band (Fig.7). When the signal is 100 times amplified, the gain is 1, and the filter cutoff frequency is 7.5 Hz. The parameters are selected as $a_i = 2^{0.5}$, b_i=1, Q=0.707, c_1=1 μF, and c_2 =2 μF. The R_1 and R_2 can be expressed as follows.

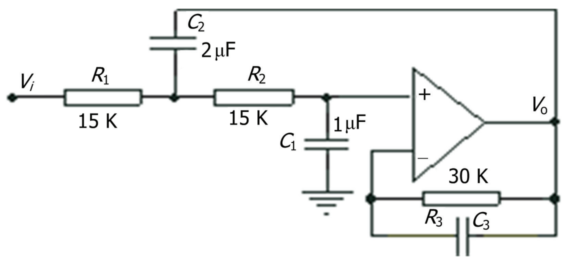

Fig.7 The second order low-pass Butterworth filter.

$$R_1 = b_i/(\omega^2 R_2 c_1 c_2) \qquad (1)$$

$$R_2 = \frac{a_i \pm \sqrt{a_i^2 - 4b_i(1 - k + c_1/c_2)}}{2\omega_c c_1} \qquad (2)$$

The R_1 and R_2 about 15 kΩ are calculated by replacing the known parameters.

5 High-linearity analog optocoupler isolation circuit

The HCNR201 analog optocoupler consists of a high-performance AlGaAs LED that illuminates two closely matched photodiodes[8], thus ensuring its high linearity and stable gain characteristics of the optocoupler in analog signals isolation.

5.1 Operation theory of HCNR201

The HCNR201 unipolar circuit topology is shown in Fig.8. An external amplifier (A_1) and the photodiode PD_1 comprise feedback loop. The PD_1 is used to monitor the light output of the LED and automatically adjust the LED current for compensation of any non-linearities. The output PD_2 converts the stable light output of the LED into a linear current, which can be converted back into a voltage by A_1.

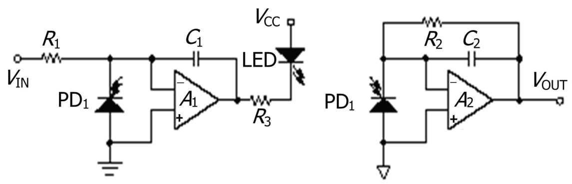

Fig.8 The unipolar circuit topology.

The PD_1 works as a current follower in the unipolar working mode, and the temperature compensation and the linearity improvement are implemented by maintaining zero potential of A_1 inverting input. Stated briefly, amplifier A_1 adjusts the LED current (I_F), and therefore the current in PD_1 (I_{PD1}), to maintain its "–" input terminal at 0 V. The relation between the input current and the output voltage is as follows.

$$I_{PD1} = V_{in} / R_1 \qquad (3)$$

$$V_{out} = I_{PD2} \times R_2 \qquad (4)$$

$$K = I_{PD2}/I_{PD1} \qquad (5)$$

$$V_{out}/V_{in} = K \times (R_2/R_1) \qquad (6)$$

The I_{PD1} is exactly proportional to V_{in}, thus giving a very linear relationship between the input voltage and the photodiode current. The ratio of V_{in} to V_{out} is constant, and independent of the light output characteristics of the LED.

The bipolar circuit topology is shown in Fig.9. The AR1 as an inverting amplifier is with the gain 1, and applied to 3-V DC bias voltage input. The relationship of V_{in} with V_{o1} is expressed as.

$$V_{o1}=-(R_7/R_6)V_{in}+(1+R_7/R_6)V_A \quad (7)$$

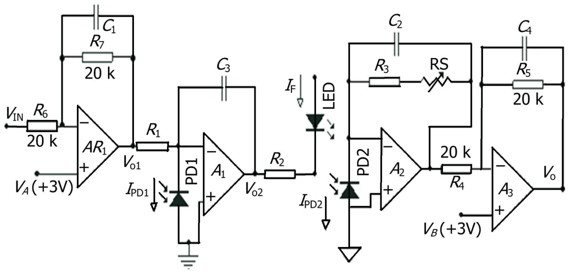

Fig.9 High-linearity analog optocoupler isolation circuit.

On the condition of $R_6=R_7$ and $V_A=3$ V, Eq.(7) is simplified as $V_{o1}=6-V_{in}$. The appropriate quiescent point of HCNR201 is set up to 6 V, thus leading to simplify circuit design and achieve better bipolar signal isolation.

In the actual design, when each isolation circuit front-end has its own power supply, the 3-V bias voltage of V_A and V_B should be provided by precision voltage reference sources to reduce deviation of each channel 6-V quiescent point, thus enhancing the interchangeability of each isolation circuit.

5.2 High-linearity analog optocoupler isolation circuit parameter selection

Here, we discuss the value of R_1, R_2 and R_3 in Fig.9. I_F and I_{PD1} are expressed as.

$$I_F=(12-V_{LED}-V_{o2})/R_2 \quad (8)$$

$$I_{PD1}=V_{o1}/R_1 \quad (9)$$

Since $I_{PD1}=0.005I_F$ (typical value in parameter Table), Eq.(10) is obtained

$$V_{o1}/R_1=(12-V_{LED}-V_{o2})/200R_2 \quad (10)$$

On $R_1=200R_2$, $R_3+RS=R$, $V_{o1}=12-V_{LED}-V_{o2}$, and $R_2=V_{o1}/I_F$.

R_2 is selected to achieve an LED current of about 10 mA at the nominal input, and linear area of V_{o1} is 6 V, so $R_2=600$ Ω, $R_1=R=200R_2=120$ kΩ.

HCNR201 is the current-driven device, and LED quiescent current is about 10 mA, leading to that driving current of amplifier (A_1) is more than 10 mA.

6 Signal isolation line test and discussion

Signal source of 10 μA constant-current source and precision resistance box is used to simulate the superconducting coil output signals. It is important to monitor supercritical helium temperature, as it can offer reference for signal of quench, therefore resistance box is selected as 4.2 kΩ when debugging the circuit. After full test of the circuit, the resistance box is adjusted to 4-, 3-, 2-, 1-, and 0.5- kΩ in turn to determine the circuit linearity and accuracy from superconducting critical temperature to room temperature. Test results show that the circuit accuracy is within 0.5‰, 1‰,and 5‰, when the resistance is higher than 3 kΩ, 1–3 kΩ, or lower than 1 kΩ.

The EAST device design requires the liquid helium temperature measure error should be less than 10 mK[3]. From Table 1, the thermometer sensitivity is about 10 Ω / 10 mK at the liquid helium temperature, and the measure accuracy is less than 0.5‰, meaning that the resistance measure error is less than 2.1 Ω (4200×0.5‰=2.1). So the circuit can measure the temperature data and quench signal accurately during the cooling and operating.

Figure 10 shows the first cooling down procedure of the TF magnet system. Two kilowatts per 4.5 K cryogenic and refrigerator system cooled down the 200-t superconducting magnets to the superconducting phase after 14 days (March 4).

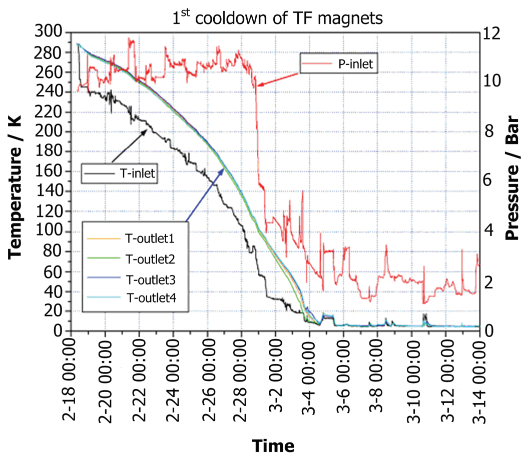

Fig.10 First cooling down procedure of the TF magnet system.

The superconducting coil charge was made on the PF12 as one of four big PF coils. The current was set to 1 kA at the rate of ~50 A/s. Followed by 260 charges on other PF coils and central solenoid, the current was up to 2 kA at the charge rate of 2 kA/s. The longest pulse for the TF is 5000 s. The TF magnet system was charged up to 8.2 kA, the toroidal field at the major radius of 1.7 m reached 2 T[9–12].

The temperature detection circuits work accurately and safely whether in cooling or operating process. So the cryogenic and refrigerator system can strictly control cooling rate and the temperature difference between the various device components and keep the stable critical temperature to prevent the quench of the low-temperature superconducting coils.

7 Conclusions

In this paper, the composition, the working principle, and the testing results of low-temperature superconducting coil temperature detection circuit are introduced. The weak voltage of a critical superconductor temperature can be extracted and amplified by pretreatment circuits and high-linearity analog optocoupler. The temperature detection circuit works accurately and safely whether in cooling or operating process. This technique is effective for the coil temperature detection.

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